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Influence of heat treatment on microstructure and tensile properties of conventionally cast and directionally solidified superalloy CM247LC

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Abstract

The influence of heat treatment on the evolution of γ′ and tensile properties of the conventionally cast (CC) and the directionally solidified (DS) superalloy CM247LC has been extensively investigated. The tensile strength of the CC and the DS alloys is dependent upon aging and solution treatment condition. In the case of the CC specimen, the aged condition (HTA condition) has higher strength than the solution treated and aged condition (HTSA condition) at low temperature (at and below 650 °C). On the contrary, HTSA specimen shows higher strength at high temperature (at and above 871 °C). Shearing of γ′ by coupled dislocations is a principal deformation process at the low temperature, and cutting of fine secondary γ′ plays an important role at an early stage of deformation in the CC specimen. The HTSA condition exhibits higher strength than HTA condition in the DS specimen in all temperature range. High tensile strength of the HTSA specimen at high temperature is found to be attributed to the rafting of γ′.

Keywords: CM247LC; Conventional cast; Directionally solidified; Tensile properties

1. Introduction

The size, morphology and volume fraction of γ′ particles have been shown to affect the mechanical properties of superalloys [1–3]. Primary γ′ particles precipitate during aging treatment and secondary γ′ particles form during cooling from aging temperature in a Ni-base superalloy [4]. A very fine secondary γ′ precipitated in matrix channel had a significant effect on creep strength of the Ni-base superalloy.

Though superalloy CM247LC was developed for a directional solidification by modification of Mar-M247 alloy, it employed in integral turbine wheel as an equi-axed poly-crystal [5]. The effect of heat treatment on the mechanical properties of superalloys has been investigated widely, but most of them are concentrated on creep properties [6], study on tensile behaviors is limited. The effects of grain shape and heat treatment on the tensile behavior of the superalloy are not well known. In the present study, tensile behaviors of the CC and the DS CM247LC at various temperatures have been studied.

2. Experimental

The conventionally and the directionally solidified CM247LC specimens 13 mm in diameter were investment cast under vacuum. Grain size of the CC specimen was about 1 mm and uniform. DS specimens were cast with a withdrawal rate of 4 mm/min in Bridgeman type furnace. The cast specimens were subjected to two different heat treatments: 1) aging treatment at 871 °C for 20 h (HTA condition), 2) solution treatment at 1260 °C for 2 h + 1st aging at 1079 °C for 4 h + 2nd aging at 871 °C for 20 h (HTSA condition).

Tensile tests were carried out in air at 25 °C–982 °C with strain rate of $8 \times 10^{-5}\ s^{-1}$. Cylindrical specimen of 6 mm gauge diameter and 25 mm gauge length was employed for tensile tests. The microstructure of the specimens were examined on SEM. Samples for SEM microscopy were prepared metallographically and etched by Kalling's reagent and chromic acid solution. TEM wafers were cut parallel to the loading axis. The foils were then polished in an electrolyte containing 10%

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perchloric acid and 7% glycerin in ethanol at 40 mA and −20 °C in a twin jet electro-polisher.

3. Results and discussions

The size, shape and distribution of γ′ particles in the CC and the DS specimens under HTA and HTSA conditions are displayed in Fig. 1. The conventionally cast HTA specimen was composed of split cube type primary γ′ and very fine secondary γ′ of 0.05 μm size which precipitates in the matrix channel. Edge length of primary γ′ particle ranges from 0.3 to 0.9 μm. The directionally solidified HTA specimen has split cube type primary γ′, but a little amount of secondary γ′ precipitates in this condition. Both the CC and the DS specimens under the HTSA condition have similar γ′ morphology. Uniform cubic primary γ′, whose size lies in the narrow range of 0.3–0.5 μm, forms in the specimens. It means that almost all the primary γ′ particles in dendrite and even a part of eutectic γ′ dissolved during the solution treatment, and re-precipitated during the subsequent cooling. It was difficult to find the fine secondary γ′ particles in the HTSA specimens.

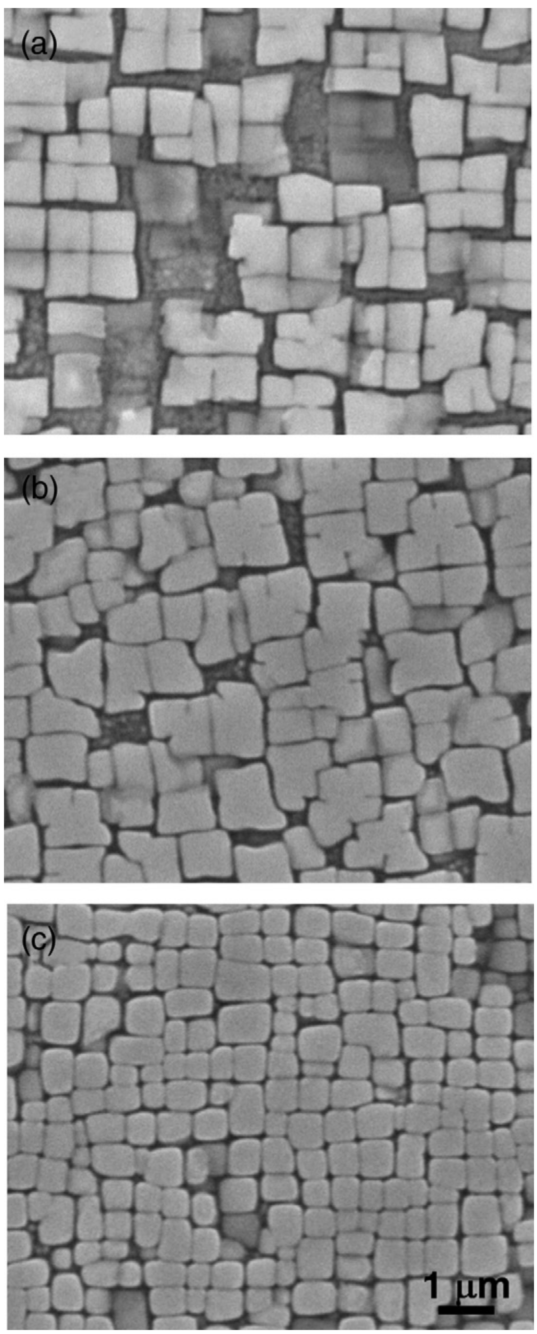

Fig. 1. SEM micrographs of heat treated CM247LC (a) CC, aged, (b) DS, aged, (c) DS, solution treatment and aged.

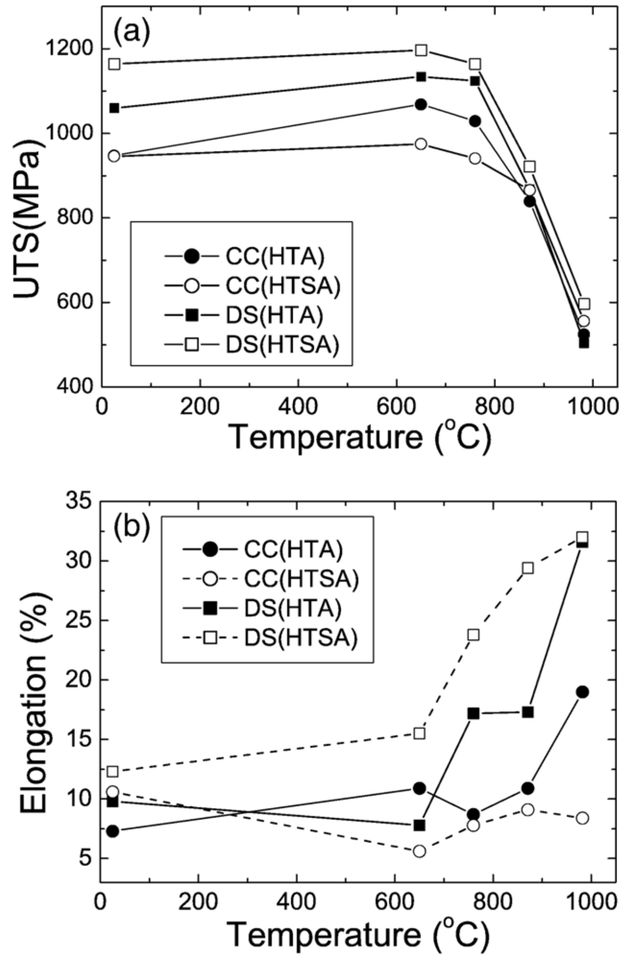

Fig. 2. Effect of heat treatment on the tensile properties of the CC and the DS CM247LC.

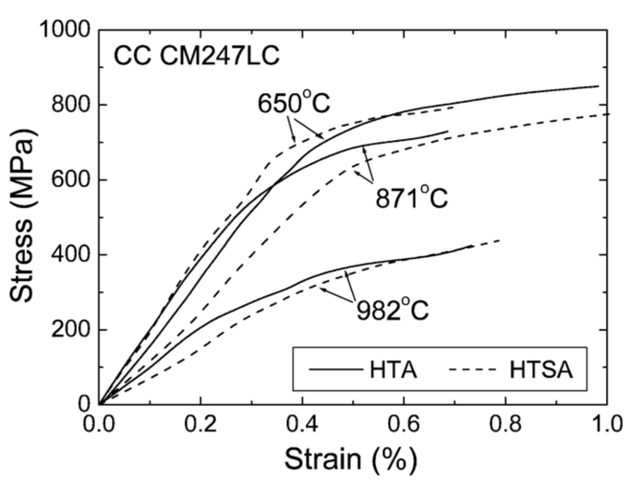

Fig. 3. Effect of heat treatment on the tensile curves of the CC CM247LC alloy.

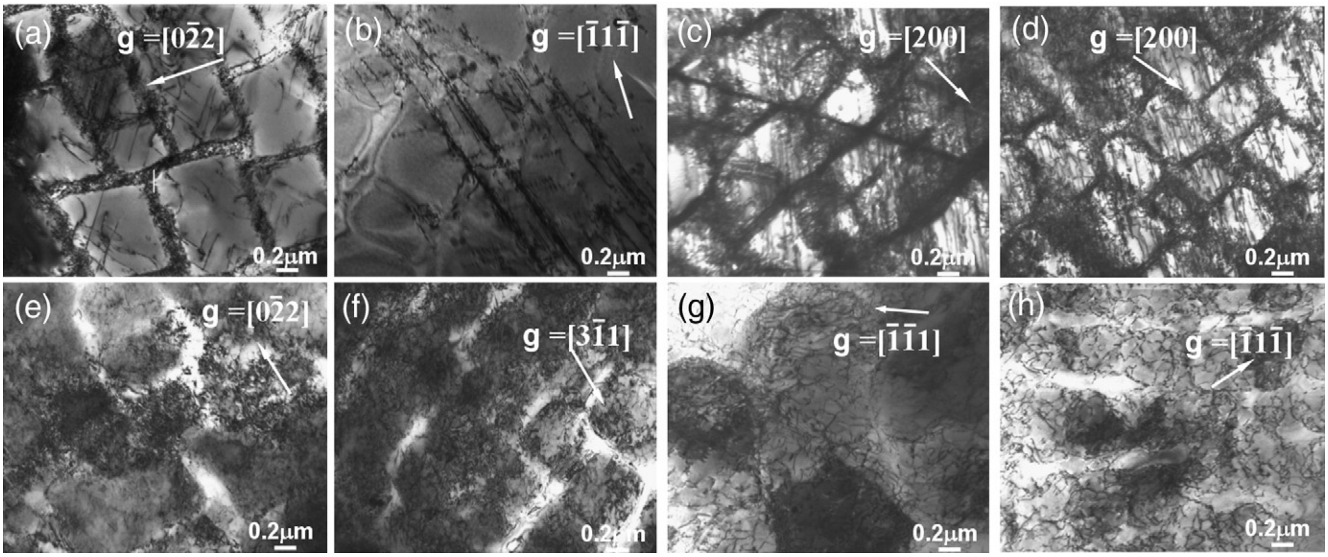

Fig. 4. TEM micrographs of CM247LC alloy tensile tested at 650 °C (a–d), 871 °C (e, f) and 982 °C (g, h), (a) CC, HTA, (b) CC, HTSA, (c) DS, HTA, (d) DS, HTSA, (e) DS, HTA, (f) DS, HTSA, (g) DS, HTA, (h) DS, HTSA.

Tensile properties of the CC and the DS CM247LC with the HTA and HTSA conditions are shown in Fig. 2. The tensile strength reaches a peak value at 650 °C, and then decreases with increasing temperature in all test conditions. In the CC specimen, tensile strength of HTA condition is higher than that of HTSA state up to 760 °C, but HTSA condition shows higher strength than that of HTA at and above 871 °C. HTSA condition exhibits higher strength than that of HTA in DS specimen in all temperature range. In the CC specimen, HTA condition reveals higher elongation than that of HTSA. On the contrary, HTSA condition has higher elongation than that of HTA in the DS specimen. The elongation tends to increase with increasing temperature, but ductility minimum appeared at 650 °C and 760 °C depending on the test conditions.

Tensile stress–strain curves of the CC specimen under the two heat treatments are shown in Fig. 3. The HTSA condition reveals higher stress than HTA condition in low strain up to 0.4–0.5% at 650 °C, but the HTA specimen shows higher tensile strength due to the higher strain hardening rate.

Fine secondary γ′ particles in the matrix channel were sheared at low strain. Relatively high strain hardening rate of HTA specimen is attributed to the large γ′ which is hard to be sheared. Deformation mechanism of shearing at low temperature is changed to thermally assisted dislocation movement at the higher temperature.

The dislocation microstructures of the specimens tested at 650 °C are shown in Fig. 4. In the CC specimen, dislocation density in γ channel is high, and γ′ is sheared by dislocation pairs under the HTA condition. Fine γ′ in the matrix channel is sheared in the early stage of deformation. Dislocations are trapped at the γ/γ′ interface, and dislocation density increases with further deformation. Stress concentration at the γ/γ′ interface causes cutting of primary γ′. But, the entire particle is not sheared by slip band, and thus deformation of the HTA specimen is homogeneous. The high density of dislocation at the γ/γ′ interface and matrix channel results in high strength. Movement of dislocation in HTSA specimen concentrates within several slip bands that shear γ and γ′. Therefore, the deformation is inhomogeneous and elongation is very low.

Directionally solidified HTA specimen is deformed by multiple slip at 650 °C. Concentration of dislocation into the slip bands causes low ductility. The HTSA specimen shows numerous dislocations with <112> line direction even though there are dense dislocation tangles in the matrix. Ductility minimum of the CC and DS specimens at 650 °C is related with slip band and localized deformation.

Microstructure of specimens tested at 871 °C and 982 °C are shown in Fig. 4. Tangles of short misfit dislocations form at the γ/γ′ interface in both CC and DS specimens. The formation of the misfit dislocation results from the partial loss of coherency at the γ/γ′ interface [7]. The deformation of the HTA specimen tends to be homogeneous, and this leads to large elongation at the high temperature. The shape of γ′ particle in the HTSA specimens has changed remarkably during the high temperature tensile testing. The rafting of γ′ particles in the HTSA specimens was observed at and above 871 °C. It means that the stability of γ′ particles at the high temperature is higher in the HTA condition than that of HTSA condition. The driving force for rafting is proportional to the misfit strain. The loss of coherency at the γ/γ′ interface reduced the driving force for directional coarsening in the HTA specimen.

It is well known that the rafted structure of γ/γ′ improves creep properties of superalloys at high temperature because dislocations can no longer climb around the lamellar γ′ structure [8]. Both of the CC and DS HTSA specimens exhibit higher strength than HTA conditions that the rafting of γ′ was not evolved during the testing. It can be deduced from the above analysis that the rafting of γ′ increases tensile strength of the alloy at high temperature.

4. Conclusions

1. Shearing of γ′ particle is a principal deformation process of CM247LC alloy at 650 °C. Fine secondary γ′ particles play an important role in tensile deformation at the low temperature. Ductility minimum of the CC and the DS specimens at 650 °C resulted from the formation of the slip band and localized deformation.
2. Tangles of short misfit dislocations form at the γ/γ′ interface in both of the CC and the DS specimens at and above 871 °C. It is found that the stability of γ′ particle is higher in the HTA condition because the rafting of γ′ particle occurred in the HTSA specimens during the tensile testing at the high

temperature. The rafting of γ' leads to the increase in tensile strength of superalloy CM247LC at high temperature.

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